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PRESERVATION AND STORAGE OF SOUND RECORDINGS

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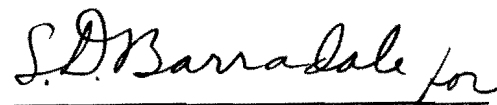
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## ABSTRACT

This report reviews the work accomplished during this report period. This work includes: (1) laboratory measurements of the linearity of visco-elastic mechanism of Vinyl, (2) measurement of Poisson's Ratio for Vinyl, (3) measurements of increase in noise level caused by accelerated aging, (4) results on fungus studies, (5) additional work on the evaluation of the literature for magnetic tape, for design of tests on tape and the establishment of criteria for library air conditioning and sound record disc jacket design, (6) and a list of the records received to date.

This report covers project activities and accomplishments through April 1, 1958.

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## I. INTRODUCTION

This is a study of the shelf aging of sound recordings, both discs and tapes, directed towards the establishment of optimum storage techniques and environments for preserving such sound records. The proposed program for this study was outlined in the Progress Report dated December 31, 1957.

With reference to the Program Breakdown, Appendix A, p. 16 foll, of the Progress Report dated December 31, 1957, Phase I has been completed with the exception of item (C) which was eliminated early in the program and Phase II is approximately 30 per cent complete. Remaining work in Phase II includes completion of creep tests, measuring the effects of cycling temperature and humidity, and evaluating the results of accelerated aging tests.

The work done during this period has been the initiation of quantitative studies of both acetate and vinyl discs, a literature study of magnetic tape problems, and an examination of means for predicting warp due to gravity loadings. Additional information concerning disc formulation obtained during the period together with the continuing literature search has determined many of the basic parameters of the optimum storage environment. The laboratory work in progress will check these conclusions and attempt to contribute additional detail as well as to enable rational estimates of useful life of sound recordings to be made.

A major gap in our knowledge is the importance of warp of vinyl discs due to gravity loadings (as distinguished from thermal or chemically induced warp). An attempt is being made to develop formulae for prediction of the magnitude of long time warp due to mechanically induced stress from parameters measured in short time tests. The necessary laboratory work required for theoretical analysis has been accomplished and further work to develop estimates of the magnitude of cold flow as a function of time based on time-temperature superposition theory is underway.

## II. LABORATORY WORK ACCOMPLISHED DURING PERIOD

### A. Creep Measurements (Vinyl discs)

Stress superposition tests have been completed, and the remaining measurements to establish the master time-temperature superposition curve are underway. As requested by Professor Lee (see "Deformation and Creep of Recordings", by E. H. Lee, appendix I) this experiment was made to determine if the material is linearly visco-elastic. It should be noted that this material property is required in the simplified theory mentioned in his paper. Figure 1 is a graphical presentation of the results. These measurements show that the material approaches the ideal linear-visco-elastic material, within a very high degree, within the range investigated.

It should be pointed out that the boundary conditions simulated, in carrying out this experiment, conform more nearly to those which might be encountered in storing a record in the off-vertical position, than the alternate possibility mentioned in the paper corresponding to a clamped support at the center of the record. In addition, it was felt that loads of sufficient magnitude were required to produce deflections comparable to at least ten times the thickness of the record, in order to produce the magnitude of cold flow, in a sufficiently short period of time. Five tests were started, but the failure of a linear variable differential transformer

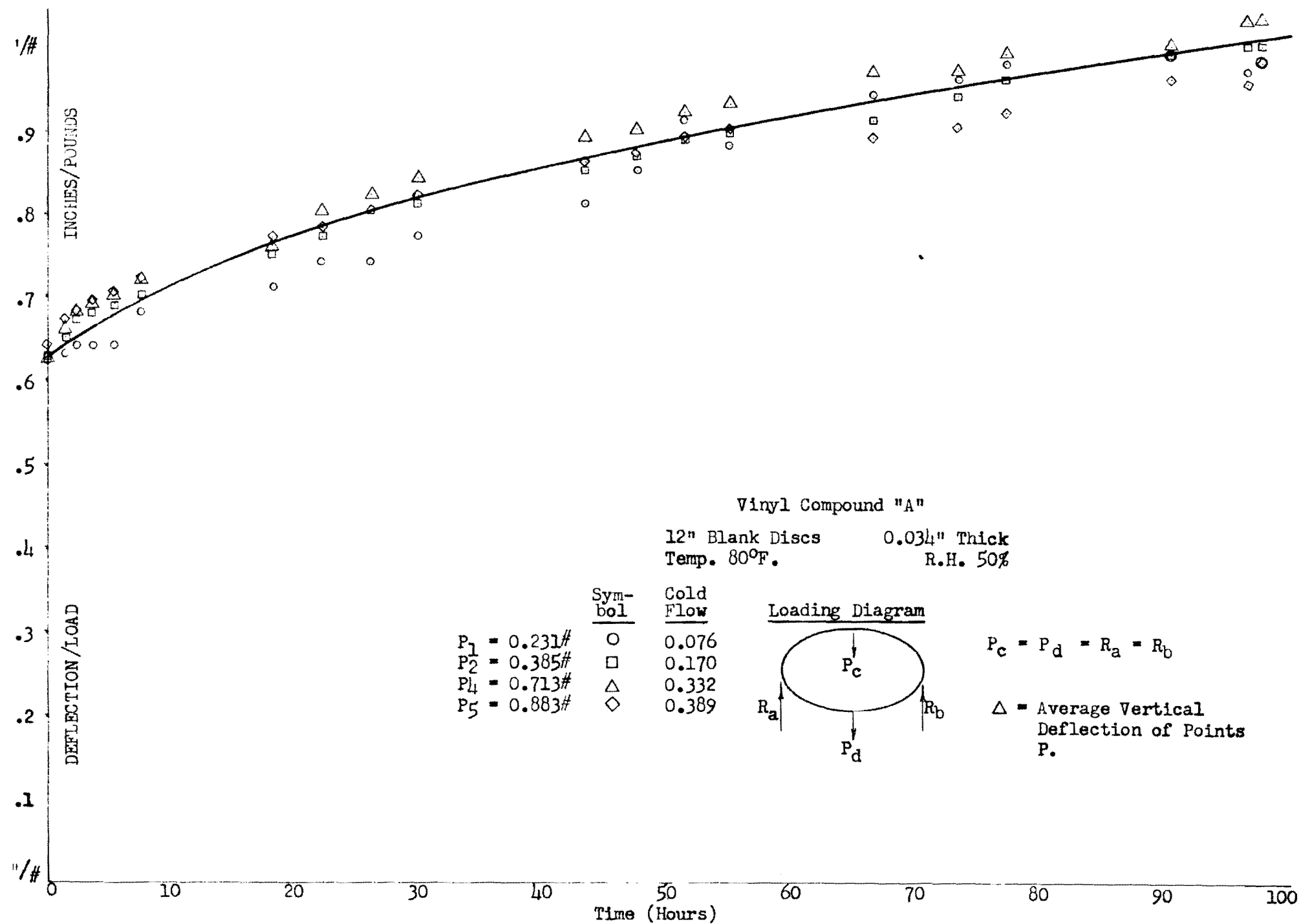


FIG. 1 STRESS SUPERPOSITION TEST (721-2)

eliminated one of the specimens. The remaining data, however, clearly demonstrates the linearity of this material (see Figure 1).

The test environment was carefully controlled at 80° Fahrenheit, a temperature slightly above existing room temperature, and 50% Relative Humidity, which is standard for this class of plastic materials. Creep tests are continuing at progressively higher temperatures in order to provide data for a master time-temperature-load deflection curve.

Figure 2 shows the test apparatus with the environmental control chamber raised, the notations being as follows:

- (1) P is point of application of load to disc and point of measurement of deflection
- (2) R is the reaction
- (3) Lever connects P to transformer core
- (4) L. V. D. T. is a 500 SL Shaevitz linear variable differential transformer whose primary is excited by a 6 volt power source.
- (5) Load is applied at transformer core
- (6) V. T. V. M. , the vacuum tube voltmeter, measured the secondary voltage of the L. V. D. T. through the switch box providing deflection data

#### B. Measurement of Poisson's Ratio (Vinyl Discs)

The other experiment made, in order to permit a theoretical analysis of stresses and deformations, was the measurement of Poisson's

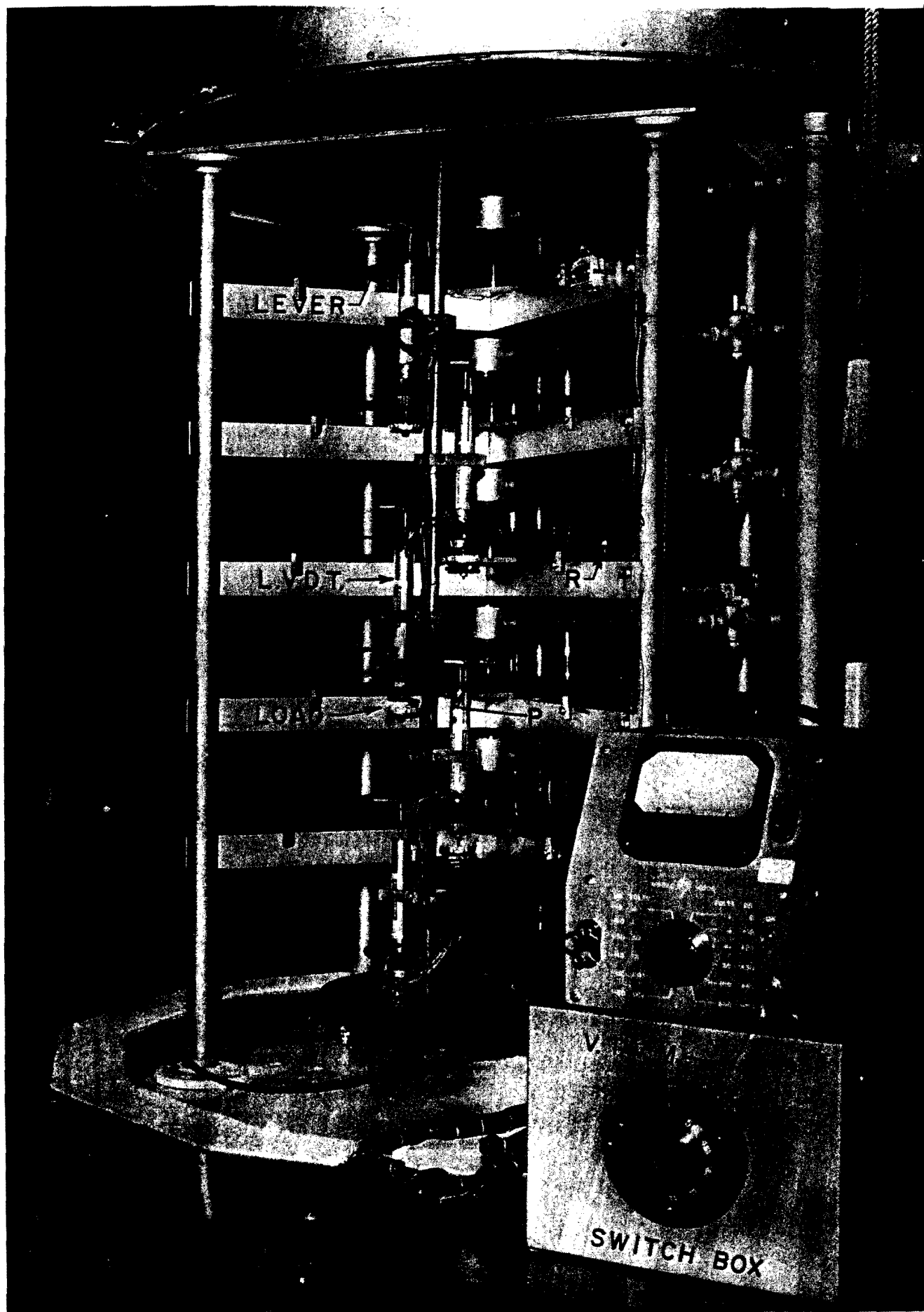


FIG. 2 DEFLECTION MEASUREMENT SYSTEM OF  
CURVED TEST APPARATUS

Ratio. This was accomplished by the technique described in "Theory of Elasticity", by S. Timoshenko, Chapter VIII, article 71. A specimen (2.00" x 0.50" x 0.034") was cut from a 12" blank of Vinyl Compound "A". This specimen was press polished and then placed in a jig which applied a uniform moment at the two ends of the specimen. A 45° optical prism was then placed at the center of the specimen. A monochromatic source of light was directed normal to the specimen surface and the reflection of the interference lines in the prism was photographed. The photograph was enlarged, angle  $\alpha$  measured, and Poisson's Ratio computed. Values measured ranged from 0.43 to 0.45 with an average value of 0.44. For a real material, this is very close to the value of 0.5 theoretically required for analysis assuming incompressibility. (See Figure 3.)

C. Accelerated Aging Monitored by Noise Measurement

The exploratory tests made it very evident that a simplified noise measuring system would be required for evaluation of the results of accelerated aging techniques. It was decided that the system should:

- (1) Separate white noise and spikes
- (2) Furnish a single number representing the white noise, automatically integrated over a given time interval (or portion of the record), which need not represent any absolute value, but could be used as an index of degradation
- (3) Count the spikes

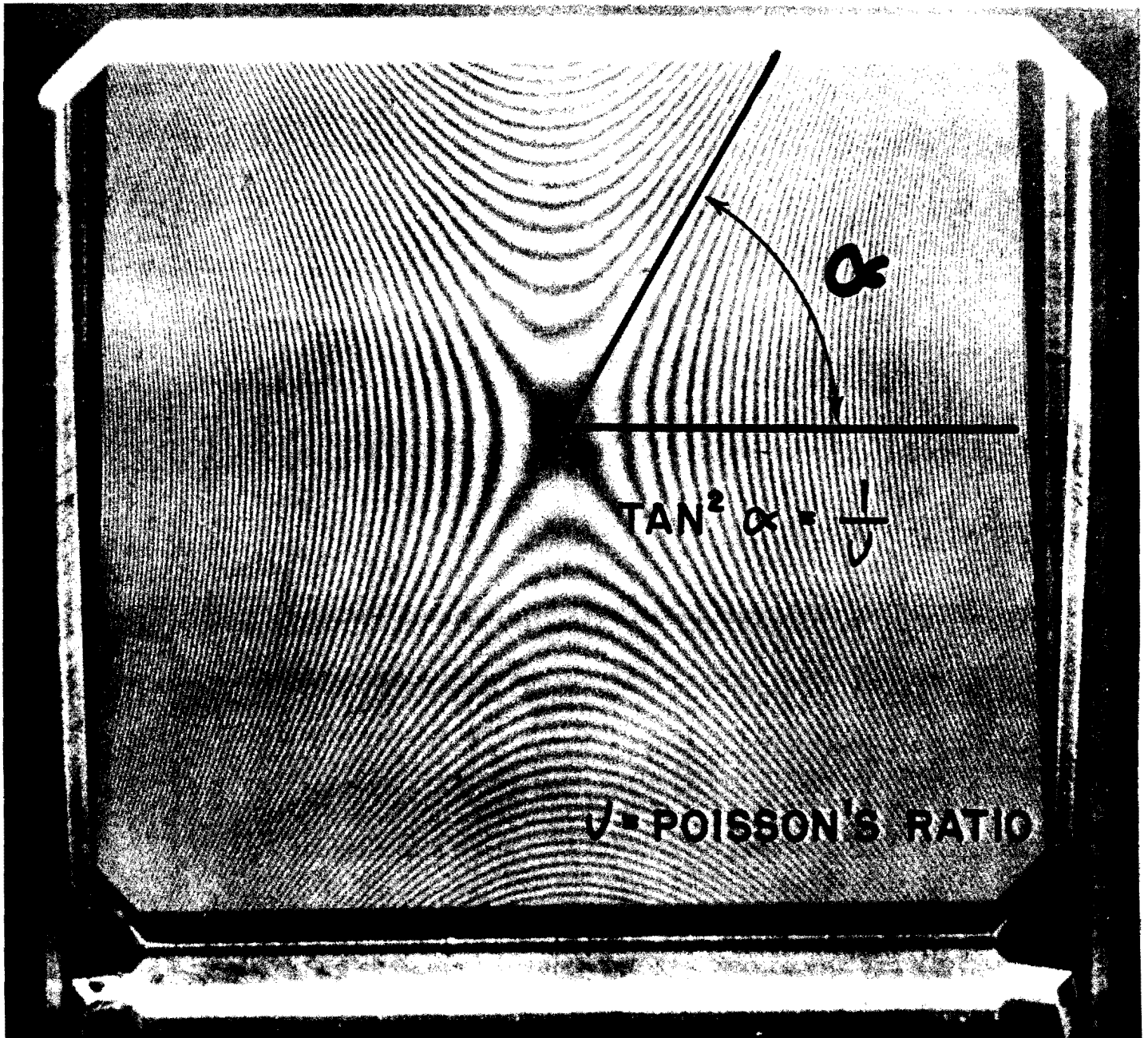


FIG. 3 MEASUREMENT OF POISSON'S RATIO BY  
PURE BENDING OF PLATE

The basis for this design was the conclusion that, in unmodulated groove records, change in white noise represents micro cracking, groove unevenness due to embrittled surfaces being chipped off, and some dimensional changes of the grooves. Spikes seem to represent dust and pits.

The equipment for making these measurements is well described in appendix II "Instructions for the Operation and Calibration of the Noise Integration and Spike Counter Equipment".

Presently, ASTM standard tests -

D 756-50 Procedure I

24 hours at 140°F & 88% R. H.

Condition at ambient, inspect and playback

24 hours at 140°F & 0% R. H.

Condition at ambient, inspect and playback

Repeat cycle

D 756-50 Procedure II

72 hours at 140°F & 0% R. H.

Condition at ambient, inspect & playback

Repeat cycle

are being conducted on acetate discs, both new specimens and specimens exposed to 2 hours ultraviolet radiation, with controls being held at ambient (approximately 70°F, 50% R. H. ) between inspection and playback.

Although these tests have not been completed, the following observations can be made from the data:

ASTM D 756-50 Procedure II. 4 cycles

- (1) No significant weight change to date and no visible exudation of plasticizer.
- (2) No increase in spikes.
- (3) Noise level has increased in record exposed to U. V. , not significantly otherwise.

For nitrocellulose plastics, this is indicative of a very carefully compounded product which is initially stable with only a first order mechanism of decomposition, the breaking of -O-NO<sub>2</sub> linkage, being significant at this stage of degradation. It will be interesting to compare the results of this test with the future test in which the humidity parameter will be changed.

ASTM D 756-50 Procedure I. 10 Cycles

- (1) No significant weight change to date and no visible exudation of plasticizer
- (2) No increase in spikes
- (3) Small, but noticeable, general increase in noise level

This is also indicative of a very carefully compounded product which is initially stable. The increase in noise level is probably due to minute irrecoverable dimensional changes due to humidity induced expansion and contraction. In the exploratory tests, decomposition

progressed rapidly at high humidity and 175°F so that some hydrolytic breakdown of the cellulose chain may also be occurring.

Changes noted to date have been minor, as would be expected from the known storage characteristics of this type of disc, and these particular tests will be continued for another two or three weeks. Temperature cycling and exposure at high humidity are scheduled for the next series of tests. Vinyl records will be introduced into the cycles at this time.

The constancy of spikes is the result of an efficient dust removal system. The "Dust Bug", a commercial product, utilizing a 10% solution of ethylene glycol in triple distilled water sparingly applied to a nylon brush which tracks the grooves followed by a mohair brush, works very well. A commercial anti-static detergent - cleaning pad system did not prove as satisfactory because it moved or left minute dust or lint particles down on the groove walls which raised both noise level and spike count considerably. There is no reason to believe that this treatment will have any effect on test results.

Also noted, was an initial high noise level in the acetate discs, probably due to the cutting process, which is "wiped out" on first playback. Another interesting phenomenon is that very fine micro cracks, which can be seen with the microscope, are not necessarily detected in playback.

D. Fungus Study

A number of records were obtained from the Library of Congress record library for fungus study. Some of these records showed signs of serious deterioration. Examination of the records revealed that certain areas were covered with fungus spores and mycelium. Upon removal of this growth, it was found that the record surface had been visibly damaged. Further investigations indicated that the fungus may be growing only on the inside of the paper jacket or on the corrugated paper used for separating records in storage and not on the record surfaces.

The first records that were examined were some of the older type, including the 1/4 inch thick Edison disc records which were popular in the early 20's. Some of the records had small cracks in the surface. Examination under the microscope indicated these cracks were filled with dust, spores and mycelium. Etchings on the surface also indicated that some fungi had grown on the jacket of the records and left an imprint of the mycelium upon the record surface.

Following examination of the records they were placed in a moist chamber for several weeks in preparation for further study. Before placing them in the moist chamber corrugated sheets of paper were cut to the approximate size of the records. These paper sheets were then moistened and inoculated with soil and airborne fungus spores. The records were then stacked between these cardboards and placed in a moist chamber or incubation box at room temperature 70-80°F for a period of four weeks.

A constant supply of fresh air was drawn into the chamber. In order to maintain a high relative humidity, a pan of water was placed in the chamber. This kept the relative humidity at 70 percent or over.

Following the incubation the records were unpacked carefully and examined with a hand lens and the microscope, for the presence of fungi on the records. The records were also examined for etchings that might have resulted from contact with fungi that were actually growing on the cardboard separators.

An abundance of fungi were noted growing on the cardboards. They included mainly species of *Penicillia*, *Aspergilli*, *Mucor* and *Rhizopus*. These fungi utilize the adhesive and cellulose as a source of food and energy.

#### 1. Results of Observations

Fungus mycelia could be seen plainly on the surface of the records with the aid of a hand lens and a stereoscopic microscope. It was also noted that the mycelium grew down, into the grooves, indicating that it was growing on the surface of the record and not just the jacket or separator. Smooth portions of records covered with fungi were further examined under a microscope. While observing the field, it was swept clean with a camel hair brush, in order to determine if any markings could be noted underneath the mycelium. It was easy to distinguish etchings made by fungus hyphae from ordinary scratches. The ordinary scratches

are in straight or curved lines. Etchings made by hyphae are irregular and appear to be more superficial and only on the surface.

The attached photograph (taken on the unmodulated edge of a black vinyl record containing a large amount of  $\text{CaCO}_3$  filler, a compound normally considered fungi resistant) shows fungi growth (a), scratches (b) and fungi etching (c). This was a new record exposed to attack for approximately three weeks. (See Figure 4.)

It will be noted that the scratch, which we know to cause noise in playback, is of the same order of magnitude as the fungal etching. This damage could have been prevented by either reducing the humidity of the environment or by use of a fungicide.



FIG. 4 FUNGAL GROWTH ON VINYL RECORD

### III. LITERATURE SURVEY AND OTHER STUDIES DURING REPORT PERIOD

#### A. Magnetic Recording Tape

A preliminary literature search has been made for the specific purpose of devising experiments and determining specimen requirements. At this time, these parameters are considered important:

##### 1. Base Material

a. Paper, paper laminate, vinyl resins, cellulose acetate and Mylar (Dupont Polyester) have been used for this purpose. Only cellulose acetate and Mylar are currently produced. It is thought that this program should be limited to these two materials.

b. The parameters to be investigated are dimensional changes, tear strength, and embrittlement.

c. The significant parameters of degradation are temperature, humidity, mechanical stress, loss of plasticizer and residual solvents, and oxidation.

##### 2. Bonding Adhesive

a. Little information has been found on this subject except that cellulose nitrate has been used. The "secrets" of magnetic tape manufacture are the compounding of this emulsion and the techniques of its application. For this reason, it is proposed to obtain tape from different manufacturers, in order to compare differences in this parameter and it

is hoped that these manufacturers will provide some information about the adhesives they use.

b. The parameters to be investigated are softening of adhesive to permit excessive loss of material by rub off during playback or adhesion to the back of adjacent layers, embrittlement of adhesive resulting in loss of material, or separation of coating from base as the result of differential dimensional changes.

c. The significant parameters of degradation are temperature, humidity, mechanical stress, loss of plasticizer and residual solvents, and oxidation.

### 3. Magnetic Particles

a. A number of magnetic materials have been used, in particular black and red oxides. For the purpose of this program, it is believed that only three grades of red oxides should be considered. These grades are commonly designated as general purpose, low noise, and high level.

b. The parameters to be investigated are changes in magnetic properties resulting from the influence of extraneous magnetic fields (including those of adjacent particles) and which are manifested as print through, erasure, attenuation and noise.

c. The significant parameters of degradation are temperature, magnetic environment, and level of original recording.

Fortunately, the magnetic degradation has been most thoroughly investigated and this study will be largely confined to compilation and evaluation of existing information and checking theory.

It should be noted here that, while disc fabrication has changed little in the last twelve years, magnetic recording tape manufacture has been continuously advancing. Part of the impetus has been from the data recording and computing field in which drop outs, holes, print through and other effects are such serious sources of error that better tape had to be developed. As a result, it will be extremely difficult to quantitatively extrapolate information gained in studies of new tape to predict behavior of tape only a few years old.

The tape requirements for the experimental program, subject to revision by the Library of Congress, are foreseen as:

- I. Base Material
  - A. Cellulose Acetate
  - B. Mylar
- II. Size Tape
  - A. 1-1/2 mil
  - B. 1 mil
  - C. 1/2 mil
- III. Size Reel
  - A. 5-inch

## IV. Manufacturers

- A. M M M
- B. Audio Devices
- C. Ampex

## V. Magnetic Material

- A. Red oxide - general purpose
- B. Red oxide - low noise
- C. Red oxide - high level

## VI. Signal Recorded

- A. None
- B. Range of standard frequencies at standard recording level ( -20 D. B. or V. U. )
- C. Tone burst tape with a range of standard frequencies separated by 10 layers of blank tape recorded at normal maximum level ( 0 to 2 D. B. or V. U. )

Appendix D summarizes, in detail, the recommended tape acquisitions. Since this is based on a survey of the field without specific knowledge of what an actual library has on its shelves, it is hoped that the Library of Congress will amend this list as required by their inventory.

B. Library Air Conditioning

An environment for the storage and preservation of organic

materials, which must be readily accessible for use, must necessarily be a compromise between the optimum storage conditions for the material and a satisfactory environment for human activity. In a real case, the economics of construction, maintenance, and use must also be considered. The logical solution to this set of problems has been the development of commercial air conditioning systems and controls that provide a desired compromise environment, which, fortunately, can provide the required temperature and humidity.

From the extensive research studies made by others as well as experience records from both the Armed Services and industry, we can establish the requirements of such an environment.

1. Oxygen

We cannot eliminate this element from the environment because of the accessibility requirement. Oxidative degradation can be reduced, however, by:

- a. Preventing photochemical catalysis by denying access of light in the 4000 angstroms (and shorter wave length) region to the material.

- b. Preventing production of oxidant (or ozone) in the stack area by proper location and maintenance of electrical equipment.

2. Temperature

The temperature should be closely controlled and maintained at the lowest temperature compatible with human requirements. Variation

of temperature is as serious as elevation of temperature (within normal limits). A temperature of 70°Fahrenheit  $\pm 5^\circ\text{F}$  is recommended with adequate air circulation to prevent development of "hot spots".

### 3. Humidity

Human considerations are not as important as the necessity for balancing different requirements of different materials. The optimum humidity is 50% R.H. and constancy of humidity is very important. A controlled system (with both drying and humidifying components) using a sensing element accurate to  $\pm 2\%$  R.H. and a response time of 10 seconds is recommended and is considered within the realm of good commercial air conditioning equipment.

### 4. Dust

Aside from its nuisance value, dust is a serious enemy of low noise level in all sound recording media. Also, when embedded in the soft plastic, it can cause permanent damage to the record grooves. For these reasons, a dust removal system, in both the recirculating elements of the air conditioning system as well as in fresh air intake, is recommended.

### 5. Airborne Acidic Compounds

Phase I gross effects studies showed that high concentrations of  $\text{SO}_2$ , in the presence of moisture, significantly damage the acetate records. A study of the literature also indicated damage to vinyl records resulting from  $\text{SO}_2$  attack on heat and light stabilizing ingredients and on calcium carbonate fillers. Evaluated in terms of the recommended storage

environment, described in III.B., and with the use of record envelopes which provide stagnant air at the record surface, it is not felt that sufficient  $\text{SO}_2$  will be available to cause damage under these conditions. Commercial air scrubbers are available which will positively eliminate this factor but, at the present time, it is not certain that their cost is justified. Further study is needed to evaluate this.

In summary, a sound record library should have an air conditioning and lighting system which will:

- (1) Prevent the presence of the ultra violet and short wave length visible light portions of the spectrum in the playback or storage area.
- (2) Not have electric equipment which spark and generate ozone in the storage or playback area.
- (3) Have a temperature of  $70^\circ\text{F}$  controlled to  $\pm 5^\circ\text{F}$ .
- (4) Have a humidity of 50% R.H. controlled at  $\pm 4\%$ .
- (5) Have adequate air recirculation.
- (6) Have a dust removal system in both fresh air intake and air recirculation systems.

In addition, alkaline air scrubbers on fresh air intake are desirable.

#### C. Record Jacket Design

The study of record jackets has provided the following requirements for a desirable jacket for both acetate and vinyl discs:

- (1) It should not be made of a cellulosic material.
- (2) It should not contain a volatile solvent or plasticizer.
- (3) It should not develop a static charge when rubbed across a sound disc.
- (4) It should be relatively insensitive to humidity.
- (5) It should contain a fungicide which will be compatible with sound disc material.
- (6) It must be stiff enough not to wrinkle or crease and to enable record to be inserted or removed without sliding the jacket across the record face.
- (7) It must not be so stiff that it will deform the record by warping of the jacket.
- (8) It should provide a stagnant air pocket on the record face during storage.

An evaluation of different materials for this purpose is being made. Also, the idea of using a relatively inexpensive sealed envelope and a stiff jacket is being considered for seldom used precious recordings. The idea of utilizing camphor as a restorative for acetate records is still under consideration. The primary question here is the mechanism of degradation, the purpose of the restorative being to supplant lost plasticizer and it appears that loss of plasticizer is not as significant as the decomposition of the cellulose nitrate itself. For vinyl records, being unplasticized, could not derive any benefit from such restorative mechanisms.

D. Result of Questionnaires

The response of the industry to the questionnaires has been very gratifying. Since this information is confidential, specific details are not given in this report. However, this material is on file and available to the Library of Congress and members of the Project Planning Committee as required. Nevertheless, it can be mentioned that the answers to the questionnaire have eliminated many of the possible parameters of degradation from consideration and have pin-pointed the significant ones. With one or two exceptions, the composition and methods of compounding sound discs by the entire industry for the past fifteen years are now known, so that the study can be limited to the behavior of those particular materials.

#### IV. LIST OF RECORDS RECEIVED TO DATE

(See appendix F, Progress Report dated December 31, 1957).

##### 1. Phase I Acetate

- |        |   |
|--------|---|
| Type 1 | <p>Thirty (30) blank discs</p> <p>15-12" double faced regulars</p> <p>15-16" double faced regulars</p>  |
| Type 2 | <p>Twenty-eight (28) records, present on both sides with unmodulated grooves at various groove pitch.</p> <p>15-12" discs at 78 RPM cut at 88, 104, 112, &amp; 120 lines per inch</p> <p>13-16" discs at 33 1/3 RPM cut at 88, 104, 112, &amp; 120 lines per inch</p> |
| Type 3 | <p>Thirty (30) standard frequency test discs</p> <p>10-12" 78 RPM cut at 104 lines per inch</p> <p>10-12" 33 1/3 RPM cut at 128 lines per inch</p> <p>10-16" 33 1/3 RPM cut at 128 lines per inch</p>   |
| 3X     | <p>Twenty nine (29) discs for constant amplitude recording</p> <p>10-12" 78 RPM cut at 96 lines per inch</p> <p>10-12" 33 1/3 RPM cut at 96 lines per inch</p> <p>9-16" 33 1/3 RPM microgroove cut at 247 lines per inch</p>  |

## 2. Phase II Vinyl

### Type 1      Blank discs (351)

180-12" discs of Vinyl Compound A

19-7" discs of Vinyl Compound A

19-12" discs and 19-7" of Vinyl Compound B

19-12" discs and 19-7" of Vinyl Compound C

19-12" discs and 19-7" of Vinyl Compound D

19-12" discs and 19-7" of Vinyl Compound E

### Type 2      Unmodulated Grooves (135)

45-12" 78 RPM cut at 88, 104, 112, 120 lines  
per inch (9 pressings of each vinyl compound)

54-12" 33 1/3 microgroove cut at 200, 240, 280,  
and 320 lines per inch

36-12" 33 1/3 microgroove cut at 200, 240,  
280, and 320 lines per inch (9 pressings of  
each vinyl compounds B, C, D, and E)

The change in records received from those originally  
requested result from revaluation of parameters (see appendix III for  
request revision) due to gain in knowledge made in exploratory testing.

## 3. Additional Miscellaneous Records Received

(1)      Selected samples of vinyl pressings from dealers

shelves - 12

(2) Old and new records of identical composition from  
Columbia - 19

(3) Stack samples for fungi tests - 10

(4) Selected shellac pressings - 10

(5) Commercial test records - 8

A "walk in" storage cabinet has been built for these test records. The records are left in the boxes in which they are received until they are needed for testing. The boxes are laid flat in the shelves and are not stacked on one another. This cabinet is relatively dust free and, since it is in an air conditioned building and has considerable volume, provides a fairly constant temperature and humidity environment for the boxes. The surfaces of records to be used in playback tests are not handled, as all manipulations can be performed by grasping the edges only. Rubber gloves are used in handling the records to prevent grease and perspiration from providing an unwanted parameter. All records used to date have been in uniformly good condition at the beginning of a test, and it should be noted that this procedure results in a minimum of record handling and dust contamination.

## V. FISCAL AND CONTRACTUAL MATTERS

Project expenditures to March 1, 1958, total approximately  
\$27,000.

APPENDIXES

## APPENDIX A

## Deformation and Creep of Recordings

by

E. H. Lee, Brown University

### Introduction.

Materials, such as some plastics, which exhibit delayed elastic response and creep when subjected to stress, in addition to instantaneous elastic response, are classed as viscoelastic. For a group of such materials, the laws governing the various types of response are linear operators, and in this case stress and deformation analysis problems can be treated relatively easily. In fact, there is a direct mathematical relation between the analysis for a linearly viscoelastic body, and for the corresponding elastic body loaded in the same way. Thus the extensive literature of the theory of elasticity can be utilized in the study of viscoelastic bodies. If a body exhibits viscoelasticity in a non-linear manner, the analysis of stresses and deformation becomes inordinately more difficult. Thus in planning an investigation of the distortion of recordings, tests to check whether linear viscoelastic relations can represent their behavior to a satisfactory degree of approximation are clearly indicated. If this is the case, then relatively simple calculations can be made to determine the deformation due to various methods of storage. Otherwise, such a theoretical evaluation will become extremely difficult. Fortunately it is easy to test for linear viscoelastic behavior by loading the recordings directly, without having to cut out standard test specimens from them. The formulation of such tests is described below.

### Linear viscoelasticity.

If single components of stress  $\sigma$  and strain  $\epsilon$  only are considered, such as tension or shear, linear viscoelastic behavior can be represented mathematically by the relation [1] \*

$$P(\sigma) = Q(\epsilon) \quad (1)$$

where  $P$  and  $Q$  are linear differential operators of the form

$$P = \sum_0^p p_r \frac{d^r}{dt^r}, \quad Q = \sum_0^q q_r \frac{d^r}{dt^r} \quad (2)$$

---

\* Numbers in square brackets refer to the bibliography at the end of this paper.

in which  $t$  is the time, and  $\sigma(t)$  and  $\epsilon(t)$  give the variations of stress and strain as functions of the time. Particular choices of the constants  $p_r$  and  $q_r$ , and of the orders of the operators,  $p$  and  $q$ , give the response to stress suddenly applied as indicated in Fig. 1. This figure also indicates the recovery when the stress is removed at the time  $t_1$ . Under constantly maintained load a law of the type (1) can determine continued creep or arrested deformation depending on the orders of the operators.

An equivalent way of specifying the viscoelastic properties is to state that the material is linearly viscoelastic, and to give the creep or relaxation curve, which respectively are the strain variation at constant stress, and the stress variation at constant strain. Such curves are another way of representing the operator relation (1), and are in fact associated with the Green's functions of the differential operators.

When the stress distribution in a three-dimensional body under non-uniform loading is studied, it is necessary to consider the viscoelastic law relating the stress and strain tensors, each with their six components. For an isotropic material this can be most simply expressed by independent operator relations for the hydrostatic component of stress and the dilatation, and the deviator or shear components:

$$P\sigma_{ii} = Q\epsilon_{ii} \quad (3)$$

$$P's_{ij} = Q'e_{ij} \quad (4)$$

with the usual subscript notation for the tensor components. Equation (3) gives the viscoelastic behavior for pure dilatation, and (4) for shear deformation. The two pairs of operators are analogous to the two elastic moduli, bulk modulus and shear modulus, which specify the properties of an isotropic elastic body.

By exploiting the linearity of these expressions, differential operator relations which are analogous to any of the elastic constants can be determined. For example, for a viscoelastic body obeying (3) and (4), the equivalent of Poisson's ratio, the ratio of the lateral to longitudinal strain in a tensile test, is a differential operator which relates these two components of strain. Such operators are obtained by formally substituting  $Q/P = 3K$ ,  $Q'/P' = 2G$ , for the bulk modulus  $K$  and the shear modulus  $G$  in the expressions relating elastic constants.

A particularly simple case arises if the material exhibits shear deformations which are large compared with the dilatation, so that the latter can be neglected and the material be considered to be incompressible. In this case the equivalent of Poisson's ratio for the viscoelastic body is equal

to a constant, one half, instead of a differential operator, and the analysis of the behavior of such a body is much simpler than for the more general body prescribed by (3) and (4).

### Stress and deformation analysis.

It has been shown [2, 3], that the problem of stress and deformation analysis for a linearly viscoelastic body can be treated by taking the corresponding elastic solution and replacing the elastic constants by the corresponding operator relations. This gives a linear differential equation to be solved for the unknown stress or displacement. The fact that a linear operator relation arises, comes from the linear operators (3) and (4), and the linear elastic analysis. It should be emphasized that only linear problems can be treated directly in this way, and that such investigations as buckling problems, which by their nature involve non-linearity and failure of the principle of superposition, must be treated by other methods.

The fact that a linear operator relation would arise between, say, an applied load and a deflection response can be used to check whether or not the material is linearly viscoelastic by examining measured deflections. The principle of superposition affords the most direct check, since this is a general consequence of the linear operator relation. For example, if a suddenly applied and maintained constant load  $w$ , gives a deflection  $\delta(t)$  which will in general vary with the time if the material is viscoelastic,  $2w$  will produce the response  $2\delta(t)$ , and so on. Thus a method of checking linearity is to use a convenient method of loading a body with a load  $w$ , and to measure the resulting variation of deflection,  $\delta(t)$ , at some convenient location. Then if the test is repeated for various values of  $w$ ,  $\delta(t)/w$  plotted against  $t$  will give a single curve if the body obeys a linearly viscoelastic law. The extent to which the curve of  $\delta(t)/w$  plotted against  $t$  changes for different values of the load  $w$  will determine the error in the approximation of linearity. In the above, deflection or load could equally well be replaced by angular rotation and moment, since the relationship between such quantities will be linear operators if the material is linearly viscoelastic.

A possible means of checking recordings is shown in Fig. 2. Identical records are clamped at their centers, and loaded with different weights placed in the corresponding position on each recording. The angular deflection at a point on the edge adjacent to the weight is measured by means of a set of mirrors and a telescope and scale. One record is unloaded, and the measurement for this must be subtracted from all the readings to eliminate the effect of the weight of the record itself.  $\delta_r(t)/w_r$  is then plotted for each record, where  $\delta_r(t)$  is the deflection due to the added weight. The spread of these curves gives the error in the assumption of linearity. The above deductions will only be correct if the loadings fall within the scope of linear plate

theory, which demands that the deflection be small compared with the thickness of the plate. If this restriction is hampering, it may be possible to devise a method of loading which gives a linear relation without this restriction, for example, by choosing a configuration which generates cylindrical bending, so that the limitations of beam theory apply, and the restriction on the magnitude of the deflection is much less severe.

In a general problem which comprises complicated stress and strain distributions, the final operator relation between, say, a load and the resulting deflection of a certain point of the body, involves the two pairs of operators (3) and (4) in a complicated manner. Thus such a check of linearity in effect involves them both. Strictly speaking only one combined operator relation is checked by such a test, and another deflection, say, would have to be investigated for absolute certainty. However, only an extremely special choice of load position and deflection measurement would indicate linearity if either of the basic operators were non-linear. For example, a test in pure hydrostatic compression would not involve the deviator relation (4), and so non-linearity of (4) would not be apparent from the measurements. In a more complicated stress distribution such an incomplete test would be virtually impossible to devise.

For cases in which the deformation is effectively incompressible, only one pair of operators appears, and this is then checked absolutely by a single deflection measurement, as long as stresses other than pure hydrostatic pressure arise.

Examples of the type of combined operator which arises in certain cases, are detailed in special examples discussed below.

If the approximation of linearity is satisfactory, then methods of deducing the viscoelastic properties must be devised in order to analyse the deflections associated with various record storage methods for various periods of time. The operators (3) and (4), or some equivalent form for them, must be deducible from measurements. Several methods of determining one type of viscoelastic relation from another have been given [4 - 7]. In many cases the stress analysis problem can be cast in such a way that the solution is given directly in terms of, say, some deflection measurement under constant load, so that in such cases measured values can be used directly in determining stress and displacement distributions.

#### Stress and strain distributions.

In considering the kinds of loading which may give rise to the warping of records while in storage, Fig. 3a illustrates a record in a jacket which

is supported at an angle  $\theta$  to the vertical. Considering the support of the disc by the jacket to be along an upper and lower arc, the weight,  $w$ /unit area, will provide a loading which for convenience can be decomposed into a body force component in the plane of the disc, and one normal to this plane. In the domain of small displacement linear analysis, these loadings can be treated separately, and the resultant stresses and strains determined by superposition. The first leads to a plane-stress slab problem with body force  $w \cos \theta$  per unit area, as depicted in Fig. 3b. The second leads to a plate problem with equivalent normal pressure  $w \sin \theta$ , as shown in Fig. 3c. The influence of the viscoelastic material properties on the stress and deformation distribution for these problems depends on the way in which the elastic constants appear in the corresponding elastic solutions, and this question is discussed briefly below.

It is well known that for plane stress and plane strain with no body forces, the stress distribution is independent of the elastic constants for problems determined by stress boundary values if the body is singly connected, or if it is multiply connected and the tractions on the separate parts of the boundary are independently in equilibrium. When a constant body force acts, the basic analysis still applies with an additional term added in the expressions for the Airy stress function (see, for example, [8] p. 25), and the above statement concerning the stress distribution still applies. Thus a problem of the type shown in Fig. 3b will have the stress distribution as for the corresponding elastic body. Displacements, however, will depend on Young's modulus  $E$  and Poisson's ratio  $\nu$ , and so their variation with time will depend on the viscoelastic properties of the material. Conversely, measurement of the deformation will determine a representation of the viscoelastic operator in the form of creep functions, since the stresses remain constant.

From the standpoint of warping, the plate problem under lateral load, Fig. 3c, is likely to be much more significant. The partial differential equation for the deflection  $w$  of an elastic plate for constant lateral load  $q$  is: (see, for example, [9] p. 88)

$$\nabla^4 w = \frac{q}{D} \quad (5)$$

where  $D$  is the flexural rigidity  $\frac{Eh^3}{12(1-\nu^2)}$ , where  $h$  is the plate thickness. The elastic constants only appear in  $D$ , so that solutions with boundary conditions prescribed in terms of deflections, lead to solutions for  $w$  in which the elastic constants appear only in the factor  $1/D$  multiplying the whole expression. For example, for a circular plate of radius  $a$  with clamped boundary, the deflection is given by ([9] p. 60):

$$w = \frac{a}{64D} (a^2 - r^2)^2. \quad (6)$$

In the corresponding viscoelastic case, a measurement of  $w(t)$  for constant  $q$  will give directly a creep function, and a method for inverting the operator corresponding to  $D$  when it appears in some other solution, for example the warping of a recording taking into account the central hole.

When the boundary conditions involve a prescription of moments, for example a hinged boundary, in addition to the factor  $D$  Poisson's ratio appears in the solution of the elastic problem, and so the corresponding operator will appear in the viscoelastic solution. For the uniform circular plate of radius  $a$ , the deflection for hinged boundaries is given by ([9] p. 62)

$$w = \frac{(a^2 - r^2)}{64D} \frac{1 + \nu}{1 + \nu} a^2 - r^2. \quad (7)$$

For the corresponding viscoelastic problem, this result involves the viscoelastic operators in a more complicated fashion. This increases the difficulty of predicting the deformation in this case, but provides a check of linearity of a more involved combination of the basic operators if this configuration is used for testing linearity. The test illustrated in Fig. 2 leads to a much more involved expression for deflection as illustrated by a related case discussed by Timoshenko ([9] p. 267). It thus appears that the linearity check suggested effectively checks both basic operators, but that the theoretical analysis of the tests is too complicated to deduce either basic operator in terms of its creep response. Simpler test configurations would be needed to achieve this. However, if incompressible analysis is satisfactory, Poisson's ratio is a constant for the viscoelastic material, and no essential difficulty arises.

### Discussion.

The methods of analysis and experiment described above provide a positive approach to the assessment and determination of viscoelastic properties of a material and their utilization in prescribing its response under various loading configurations. This approach is limited to linear situations, and, for example, large deflection theory for plates, or buckling, would require separate consideration. The variation of residual stresses and their influence on warping will fall within the scope of the theory if the resulting displacements and strains are small.

The discussion given above applies to a material at a fixed temperature. Change of the temperature will modify the viscoelastic operators. For certain materials change of temperature can be related to change of the time scale of response to stress, as discussed by Ferry and Tobolsky (this work is reviewed by Schwarzl and Slaverman [10]). For such materials the methods

of analysis described above can be applied to the determination of visco-elastic laws at different temperatures, and so of assessing warping over long periods by means of relatively short time tests.

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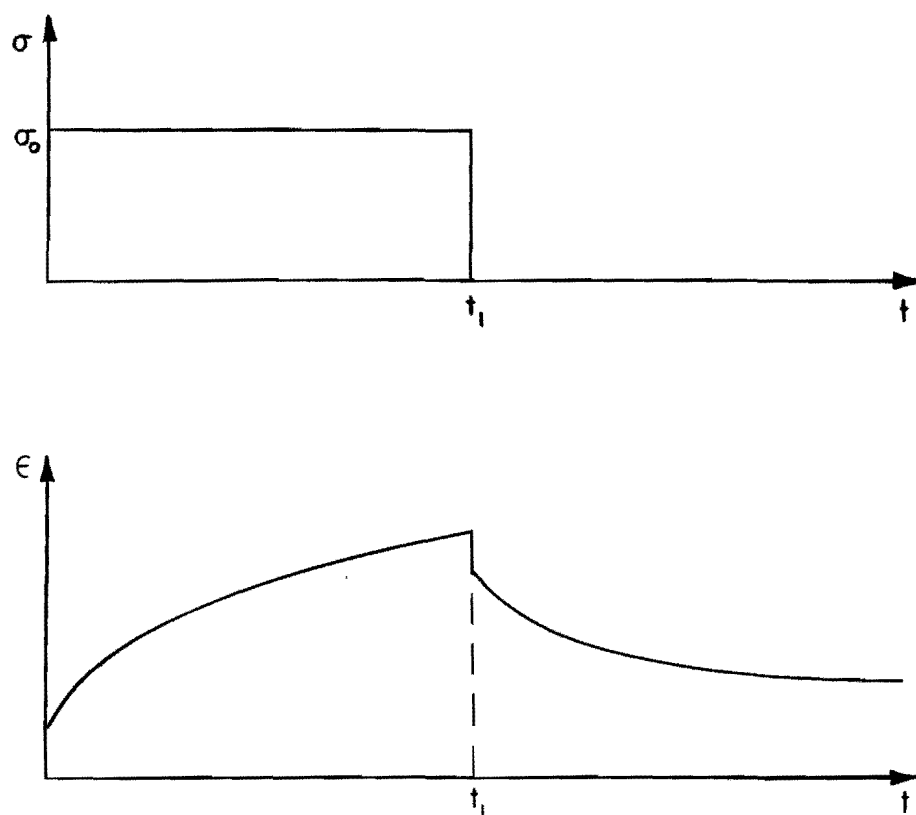


FIG. 1 RESPONSE TO LOADING AND UNLOADING

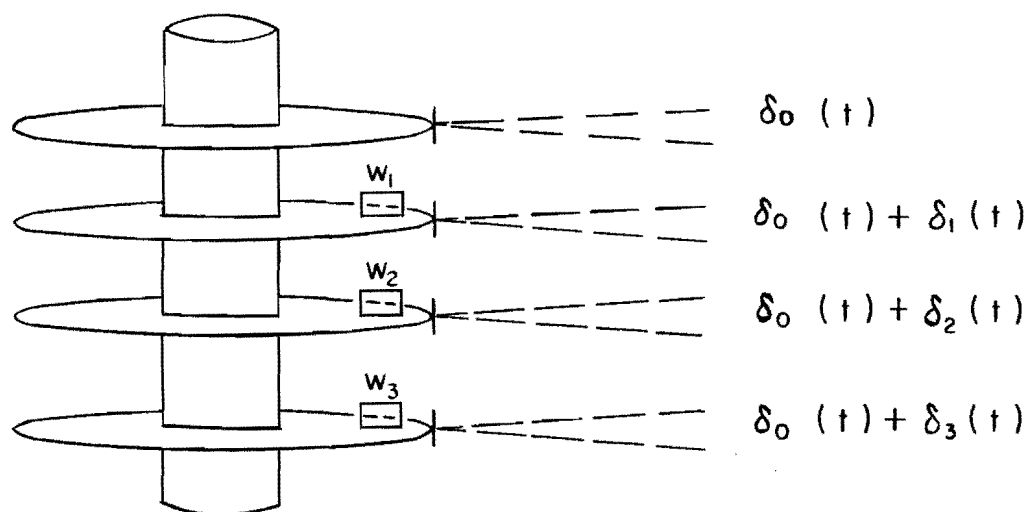


FIG. 2 TEST FOR LINEARLY VISCOELASTIC BEHAVIOR

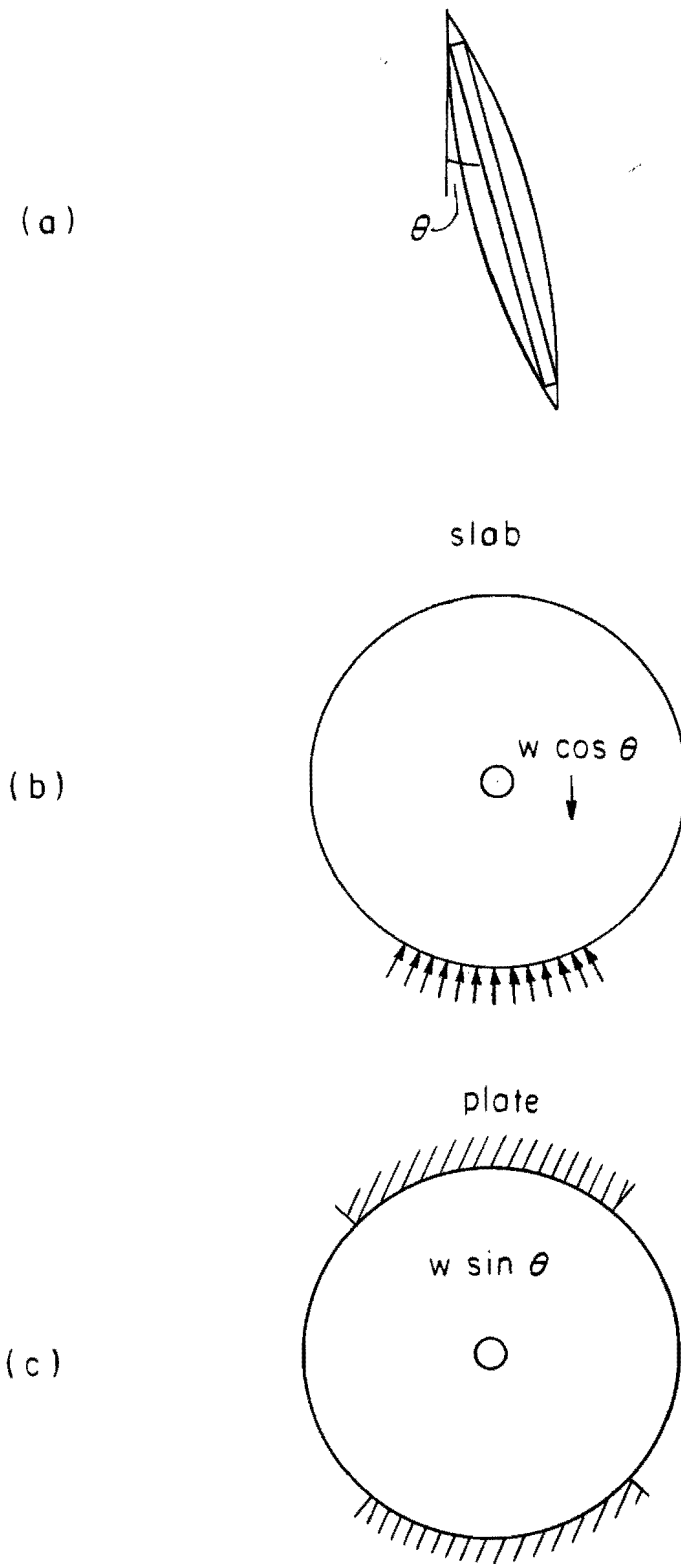


FIG. 3

APPENDIX B

## INSTRUCTIONS FOR THE OPERATION AND CALIBRATION OF THE NOISE INTEGRATION AND SPIKE COUNTER EQUIPMENT

### Description:

The noise measurements to be made consist of the counting of the noise spikes that reach a predetermined level of voltage and that occur within a ten revolution, period of a record; and the integration of all of the noise under a predetermined level of voltage that occurs within the same ten revolutions. The total noise signal is picked up from the record by the pickup, and connected into a preamplifier whose output is connected to a phase inverter circuit. One signal path, after the phase inverter, is through a rectifier circuit to a jack that leads to the pulse counter. The other path is through a limiting circuit to a gate tube, through a transformer to a full wave rectifier, and from there to an integrating circuit. The output of the integrating circuit is connected to the grid of an amplifier tube, and an Esterline Angus recorder is connected in the plate circuit of this tube to give an indication of the integrated noise.

The Tektronix preamplifier "B" supply voltage is furnished by dry cells, while its filament supply is furnished by a 6V storage battery. The Ballentine amplifier has its own internal battery pack. The Berkeley counter is complete within itself, and the integrating circuit is supplied with "B+" voltage from a regulated Hewlett-Packard power supply; "B-" voltage is supplied to this circuit by a laboratory-constructed regulated power supply.

The counter has controls that allow it to count everything that is lead into one input between a voltage excursion at the other input and the tenth following excursion. The eleventh excursion will then start the count over again. To provide the pulses for starting and stopping the counting operation, a small magnet was attached to a point on the rim of the turntable, and a magnetic pickup head was located in such a position that it would have a voltage induced into it with each revolution of the turntable. This pulse output was connected to the input of a Ballentine amplifier which amplified it to a level that would trigger the counter circuit. This method provided a period of measurement of ten revolutions of a record. A positioning arm was made that would provide a method of positioning the stylus in the same groove of the record each time that the record was tested.

The gate pulses were fed into the integrator circuit through a cathode follower probe that was connected into the counter unit. These pulses were

used to operate an interlock relay system that in turn caused the integration circuit to begin operation. After the tenth pulse cut the circuit off, the relays were locked in such a position that a reset button had to be pushed before the circuit would begin summing again. This feature was added to keep the eleventh trigger pulse from starting the summing operation again before a reading of data could be made and the integrator capacitors discharged. A pilot light indicator was connected to one of the relays in such a manner that it would give an indication as to when the circuits were counting and integrating. This feature was put on the equipment in order to alert the operator so that he would know when to take his reading from the counter.

#### Operation:

The operational procedure is as follows in the order given:

1. Turn on the counter unit and allow at least twenty minutes for warmup.
2. Turn on the Tektronix preamplifier, the Ballentine amplifier and both power supplies for the integration circuits. Be sure that both toggle switches on both supplies are in the up position.
3. Position the turntable so that the small magnet that is on the rim will be in such a position that the turntable will have to make at least  $3/4$  of a revolution before the magnet can pass in front of the magnetic pickup head.
4. Place the pickup on the record in the desired position using the pickup positioning arm for exact placement.
5. Push the reset button on the counter.
6. Turn the Multiplier switch that is located on the integrator chassis to "Discharge" and then back to the desired range for measurement.
7. Push the reset button on the integrator chassis.
8. Start the turntable.
9. Immediately take the reading on the counter when the indicating light goes off.
10. Mark identifying information on the recorder chart.

## Calibration:

### I. Diode Limiter Bias in Integration Circuit

The transformer that was used in the integration circuit starts to distort noticeably when a 1000 cps sine wave signal of 27.5V RMS is applied to its primary. A signal of 0.5 volts RMS or 0.707 peak-to-peak on the grid of the 6AK6 driver tube will cause a signal of this size to appear across the primary. The limiting diodes should be biased at a point that will cause them to start clipping at this voltage. To accomplish this, the following should be done:

1. Feed a 1000 cps sine wave signal into the input of the integration circuit, and with the gain control in a full clockwise position and an oscilloscope connected to the grid, pin 1, of the 6AK6 driver tube, observe the waveform.
2. While increasing the signal amplitude, adjust the diode bias controls for maximum bias, which will be indicated by the maximum signal that can be fed in without clipping.
3. Connect the oscilloscope to the plate, pin 5, of the driver tube, and turn the signal gain down until distortion just begins to appear.
4. Adjust the diode bias controls until both top and bottom of the waveform begin to be limited.

### II. Output Tube Bias

With no signal into the integration circuit and with the storage capacitors discharged, adjust the bias control until a 0.5 ma. reading is obtained on a milliammeter connected to the output jack. A curve that was plotted for the output tube shows that this setting will give the most linear output from the tube.

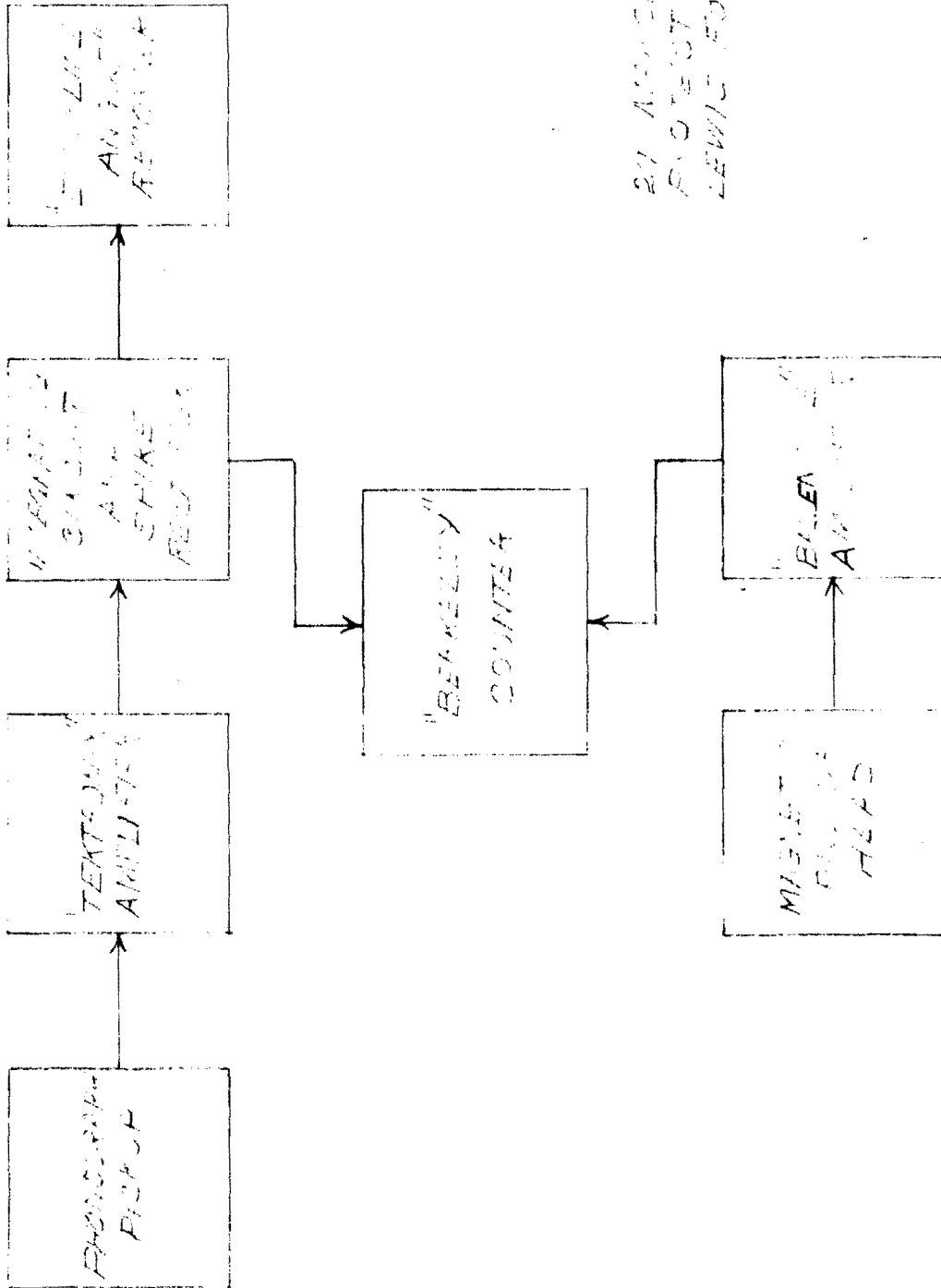
### III. Counter Adjustments

Exploratory tests showed that some noise spikes may reach 10 mv or higher, so a nominal value of 5 mv was chosen as a starting level for the spike counting. This would be 3.5 volts RMS after amplification. To adjust the counter:

1. Connect the output of the Ballentine amplifier to the "B" input of the counter.
2. Set the "Function" switch to "Count".
3. Put the "B Slope Switch" to "+".
4. Start the turntable, and adjust the "B Attenuator" and "Trigger Level" adjustment on the counter and the gain switch on the amplifier until a dependable count is obtained.
5. Set the "Function" switch to " $\frac{A}{B} \times 10$ ".
6. Feed a 3.5 volt RMS signal from a signal generator into the "A" input, and with the turntable signal still triggering the "B" input, adjust the "A Slope Switch" to "+"; adjust the "A Attenuator" switch and "Trigger Level" control until the counter just begins to count.
7. Adjust the "Display Time" control to a position that will cause the display to last less than the time of one revolution of a record.
8. Disconnect the signal generator, and connect the output of the Tektronix amplifier to the "A" input of the counter.

The equipment is now ready for operation. The "A" controls should be left in the above positions for the duration of a test series. If they are moved, the 5 mv peak counting level will be void.

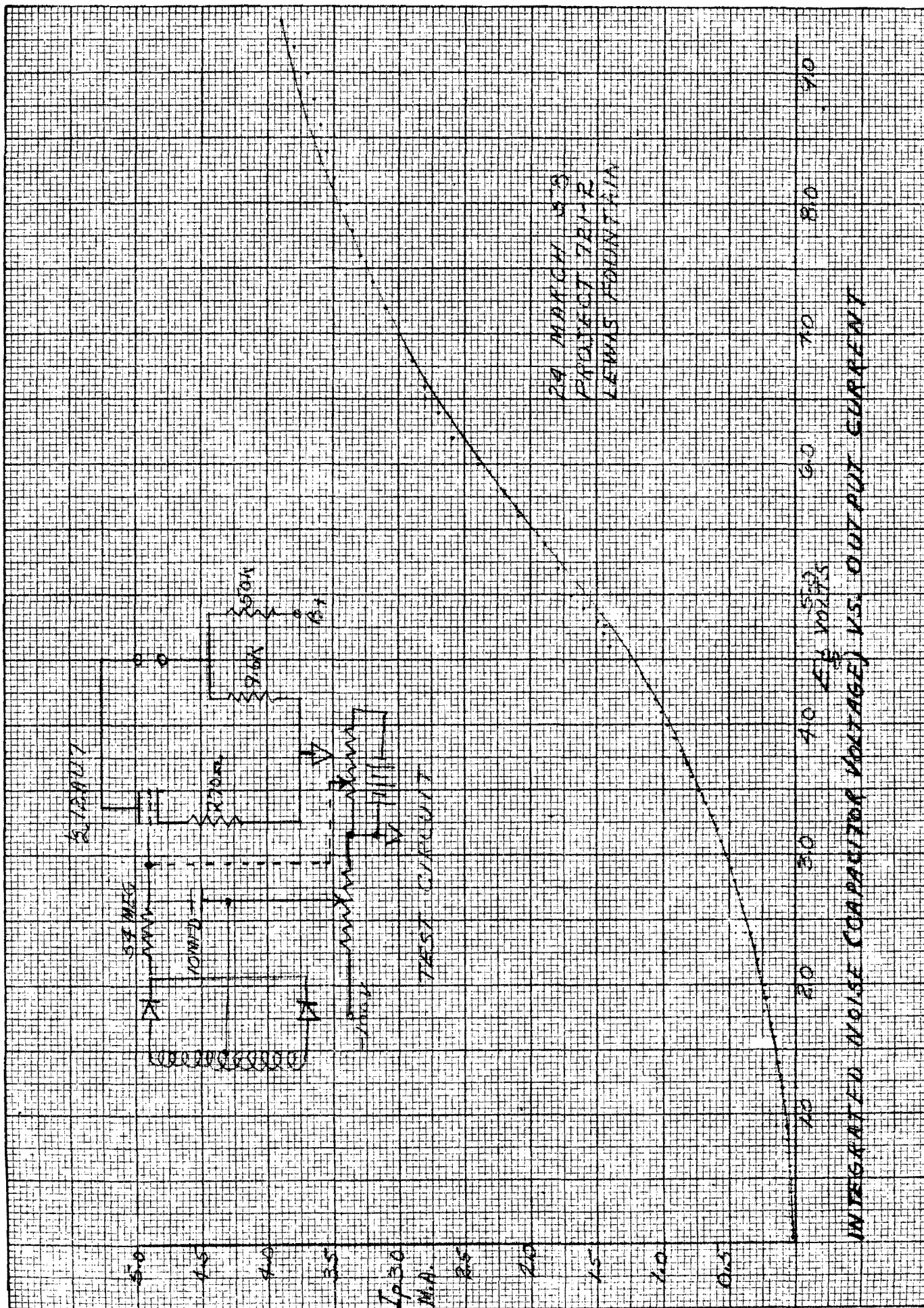
The equipment will now count all noise bursts that are 5 mv peak to peak and over as delivered from the pickup.



24 AUGUST 1943  
PROJECT ON THE  
LEWIS FOUNTAIN

BLOCK DIAGRAM OF THE "BECKLEY" COUNTER SYSTEM





APPENDIX C

COPY

SOUTHWEST RESEARCH INSTITUTE

8500 CULEBRA ROAD  
SAN ANTONIO 6, TEXAS

49

Department of Engineering Mechanics

March 19, 1958

In reply, please refer to: 721-2

Dr. Harold Spivacke  
Chief, Music Division  
The Library of Congress  
Washington 25, D. C.

Dear Harold:

I had a fine talk with Jack Wegner of Allied yesterday afternoon regarding the exact formulas for the five different vinyl compounds which we will be testing. He is going to send us a detailed breakdown of the chemicals and percentages of each of these compounds.

I also inquired as to the status of production of the vinyl records, and he informed me that only Type 1 and the 12" 78 rpm Type 2 records have been pressed. Nothing has been done with the remaining records. After a careful study of the types of tests we propose to carry out, it is now quite certain that we will need more records in the 12" pure black Vinylite compound A than any other kind. This does not mean an increase in the number of records to be pressed, since we now feel that the number of records required in the other kinds is considerably less than previously estimated. Mr. Wegner assures me that there will be no difficulty in revising the list, provided the revision is approved by you. We would like to make the following changes in the procurement list (refer to Pages 32 and 33, Progress Report dated December 31, 1957).

Type 2.    Delete:    50 - 7" 45 rpm cut at 180, 200, 240, and 280 lines per inch (10 pressings of each vinyl compound)

Add:        12" 33-1/3 microgroove cut at 200, 240, 280, and 320 lines per inch, all in 12" pure black Vinylite compound A, in an amount not to exceed the cost of the 45 rpm records which have been deleted.

Type 3.    Delete:    50 - 12" 78 rpm cut at 96 lines per inch (10 pressings of each vinyl compound).  
                          50 - 7" 45 rpm microgroove cut at 200 lines per inch (10 pressings of each vinyl compound).

Dr. Harold Spivacke

Page 2

March 19, 1958

Add: 12" 33-1/3 microgroove cut at 240 lines per inch, all in pure black Vinylite compound A, in an amount not to exceed the combined cost of the 12" 78 rpm records and the 7" 45 rpm records which have been deleted.

Type 3X. Delete: Everything.

Add: 12" blank discs, all of pure black Vinylite compound A, in an amount not to exceed the cost of the Type 3X records which have been deleted.

Type 4. Delete: Everything.

Add: 12" unmodulated groove, all in pure black Vinylite compound A, in an amount not to exceed the cost of the Type 4 records which have been deleted.

Type 5. Delete: 50 - 12" 78 rpm cut at 88, 104, 112, 120 lines per inch (10 pressings of each vinyl compound)  
50 - 7" 45 rpm microgroove cut at 180, 200, and 240 lines per inch (10 pressings of each vinyl compound).

Add: 12" 33-1/3 rpm microgroove cut at 200, 240, 280, and 320 lines per inch, all in pure black Vinylite compound A, in an amount not to exceed the cost of the Type 5 12" 78 rpm and 7" 45 rpm records which have been deleted.

We believe that the revision will in no way affect the achievement of the objectives set forth in this program; on the contrary, it is felt that by having a substantially larger quantity of the 12" pure black Vinylite compound A records, we will be able to do a much more thorough study than otherwise would be possible, without any loss of pertinent knowledge on the subject.

Mr. Wegner will not resume production of the remaining vinyl discs until he hears from you, and it will be appreciated if you would give this matter your earliest attention in giving him approval to change the purchase order as above indicated. It is noted that what we propose will not increase the cost of the purchase order; in fact, if you wish to make a ten percent cut on the "add" records which have been requested above, we feel that this would not at all hamper our test program.

Dr. Harold Spivacke

Page 3

March 19, 1958

Thank you very much for forwarding the questionnaire filled out by Columbia. They did a beautiful job in filling it out and it contains exactly the kind of information we had in mind. We are also most pleased to learn from their letter to you dated March 10 that they will be able to provide us with fresh records and old records of 1948 vintage, all from the same formula. We believe these records will be most helpful in providing check data on our other tests.

It was indeed a pleasure to visit with you and Dr. Prager during our SwRI project conference, and many thanks for your complement regarding our presentation of the project's progress. I am now preparing a progress report, which will include Minutes of this conference and hope to have it in your hands in the very near future.

With kindest personal regards.

Very sincerely yours,

M. M. Lemcoe, Manager  
Strength Analysis

MML/bb

cc: J. Wegner

APPENDIX D

## APPENDIX D

RECOMMENDED TAPE ACQUISITION  
(FOR SYMBOLS, SEE TEXT, P. 17 and 18)

<u>No. of Reels</u>	<u>I</u>	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>VI</u>
2	A	A	A	A	A	A
2	A	A	A	A	A	B
2	A	A	A	A	A	C
2	A	A	A	B	A	A
2	A	A	A	C	A	A
2	B	A	A	B	A	A
2	B	A	A	B	A	B
2	B	A	A	B	A	C
2	B	A	A	C	A	A
2	B	A	A	A	A	A
2	A	B	A	C	A	A
2	A	B	A	C	A	B
2	A	B	A	C	A	C
2	A	B	A	B	B	B
2	A	B	A	A	C	C
2	A	B	A	A	B	C
2	A	B	A	B	C	B
2	A	B	A	A	B	A
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2	B	B	A	A	A	C
2	B	B	A	C	B	B
2	B	B	A	B	C	C
2	B	B	A	B	B	C
2	B	B	A	C	C	B
2	B	B	A	B	B	A
2	B	B	A	C	C	A
2	B	B	A	C	A	A